METHODOLOGY FOR COATED INFRASTRUCTURE INSPECTION BY MOBILE POTENTIOSTAT

Bobbi Jo Merten, Ph.D.[1], Susan Drozdz, PCS[2], Cassidy Gills[3],
David Tordonato, Ph.D., P.E.[1], Jeff Ryan[2]

[1]Bureau of Reclamation, Lakewood, CO, USA
[2]U.S. Army Corps of Engineers, Champaign, IL, USA
[3]University of Mississippi, Oxford, MS, USA

ABSTRACT

A test methodology is shown for field application of electrochemical impedance spectroscopy (EIS). The method utilizes low-cost, accessible materials to secure a temporary solution cell to the infrastructure's coated surface. A laptop computer provides the power source and operating system for the mobile potentiostat during EIS data collection. This data provides a quantitative measure of the coating condition. The objective of this work is to incorporate EIS testing into standard coatings inspection to estimate remaining service life for the intact coating, which improves coatings maintenance planning for facility owners.

The first field demonstrations took place at U.S. Army Corps of Engineers projects at Ozark-Jeta Taylor Lock and Dam and Wilbur D. Mills Lock and Dam along the Arkansas River. Tainter gate structures containing a three-coat vinyl system provided optimal conditions for EIS data collection. These results were compared to laboratory EIS data for vinyl coatings to estimate the remaining coating service life. An atmospheric red lead primer with Aluminum phenolic topcoat was also tested to demonstrate the method.

This paper focuses on the most ideal circumstances for setting up and completing EIS testing in a single inspection. Variables to consider include coating type, exposure conditions, saturation level, access, and surface geometry/orientation. The mitigation of potential noise sources is also addressed to ensure accurate data and interpretation.

INTRODUCTION

The Bureau of Reclamation (Reclamation) and U.S. Army Corps of Engineers (USACE) maintain a large inventory of water management and hydroelectric power infrastructure. Reclamation is responsible for delivering irrigation water to the 17 western states and generates hydroelectric power to subsidize this work. USACE has many of the same structures but operates primarily on navigable waters and commerce has a strong influence on their maintenance strategies. Both agencies have a responsibility to maintain the health of their aging infrastructure.

The research presented here aims to provide a non-destructive method to evaluate the first line of defense against corrosion—coatings. Reclamation and USACE have many steel components to their infrastructure, including various types of gates, large diameter penstock pipelines, turbine runners, and outlet works. The cost of coatings maintenance on these components frequently surpasses the million dollar range. It is critical to achieve the maximum service life for the coatings applied to these structures before proceeding with recoat operations.

Solution vinyl coating systems provided excellent corrosion and impact resistance for immersion and alternating immersion and atmospheric services. Reclamation and USACE typically used this system for gate structures and achieved 30-40 year service lifetimes at many facilities. The thermoplastic polymer matrix wears or degrades very slowly, and it is typical for rust to first appear at areas with the lowest dry film thickness. Coal tar enamel and red lead in linseed oil with a phenolic aluminum topcoat are two additional coating systems in similar standing as they provided very long service lifetimes and currently remain on Reclamation and USACE structures. Coal tar enamel appears on immersion infrastructure such as penstock linings, and red lead/aluminum systems still in place today provide protection for atmospheric exposures.

An opportunity exists to use instrumentation to evaluate the progression of degradation for these coatings systems and calculate the remaining service life precisely and accurately. Coatings laboratories have used electrochemical impedance spectroscopy (EIS) for several decades to characterize the material degradations of coatings upon initial exposure to weathering environments (1-9). The laboratory test method is most useful for ranking coating systems in terms of expected service lifetimes. Here, the assumption is that coating degradation is progressive and its resistance to the influx of degrading species, i.e. water and ions, correlates directly to long term corrosion protection in service. Put most simply, EIS is a tool to characterize a coating's resistance to water and ion migration. This electrolytic resistance decreases throughout coating service due to degrading barrier properties and corrosion initiation (10-11). Reference and counter electrodes are used to make these measurements. The reference electrode provides feedback for the instrument, typically a potentiostat, which applies small potential changes to the film, and the counter electrode measures the current required to achieve these changes. The instrument is standardized by ASTM G106 (12). No studies are known which measure the degradation of a coating to some predetermined point of failure. However, the extrapolation of EIS data to forecast failure is theoretically valid.

EIS testing's strength is the quantification of coating degradation through regular testing during physical weathering of coated coupons. For this reason, it is a strong candidate for the evaluation of coated infrastructure during inspections. The article documents the development and demonstration of this field method.

Method Development

The work in Europe by Sonke (13) and in Canada by Gray (14) provided guidance for field EIS. Several challenges accompanied the incorporation of EIS into field use. Within the laboratory setting, the equipment includes a computer and potentiostat. The potentiostat cables are fed into a Faraday cage to shield electromagnetic noise. The goal is to minimize the presence of this noise in the data. Furthermore, the potentiostat is grounded to earth. Reasons for this include the prevention of potential drifts and sudden electrical discharges. Although the impact of testing without the two prerequisites was unknown the experiment proceeded.

The field method development also attempted to address anticipated field site access and safety concerns. Reclamation and USACE infrastructure equipment of interest tends to be large structures with poor access, often spanning sections of dangerous waterways. Therefore, the highest level of portability possible is required for the method to be useful. The instruments used were lightweight and compact. A field laptop served to power the instrument. Disposable experimental components and supplies were also selected.

It is understood that standard field inspection methods, although primarily qualitative, have advantages over a quantitative method such as EIS. Standard inspections continue to fulfill these key requirements:

- Assessment of general condition
- Identification of unique wear patterns or problem areas
- Estimation of damaged areas for repair (visible rust or defects)

Therefore, the single most needed contribution of the quantitative field method is to estimate the coating health for portions of the structure with no visible defects. As this field practice matures and data sets become large enough to interpret with statistical significance, the estimation of remaining service life will improve greatly. This new value will be a key determinant for coating maintenance decisions. As an example, a visual inspection of a structure may show that 10% of the coating requires spot repairs, but EIS data indicates the intact coating will fail within 5-10 years. It may not be economical to perform these spot repairs and instead begin budgeting for a full recoat.

This method is applicable to all types of coating exposure. To some, it may be most valuable to measure the coating health for notably corrosive or critical areas. This could be for hydraulic structures at the waterline or for immersed structures that are rarely taken out of service. Others may find it useful to monitor an atmospheric coating to attain an extra 10 or 20 years of service before recoating.

EXPERIMENTAL SETUP

Coated Infrastructure Inspection Method

The initial step in this inspection is to assess the coated steel for coating material, condition, service/exposures, and access. Figure 1 provides one USACE facility utilized for this demonstration. The top and upstream faces of the radial gate provided opportunities for experimentation. At a second USACE facility, tests were conducted on a trunnion arm near the pin, handrail structural brackets, and the upstream vertical face of the lock miter gate. Table 1 details test sites and conditions. Note that Test 2.2 had one visible defect in the test cell.

Polyethylene 100 mL beakers were used to create a field test cell. Each had been prepared by removing the bottom portion and discarding. The coating surface was cleaned with an isopropyl alcohol pad at each test site. A 1:1 ratio of marine epoxy was mixed and applied to the 0.3 cm top lip of the disposable beaker. It was then inverted and pressed firmly against the prepared surface to provide a reservoir for the test solution. The surface area for the experiment was 25 cm^2.

Following approximately 1 hour cure time, dilute salt solution (0.05 wt. % NaCl, 0.35 wt. % $(NH_4)_2SO_4$—(DHS)) was added to the test site beaker. The coating and solution were allowed to equilibrate for at least 30 minutes prior to testing.

A sponge was cut to the shape and size of the beaker and positioned against the coating to hold moisture in the event of leakage. Platinum mesh and saturated calomel electrode (SCE) were set through a rubber stopper and into the beaker. These provided a counter electrode and reference electrode, respectively. A coating defect area was cleaned to bare steel with a metal file and an alligator clip taped firmly for direct connection of the working electrode. An Ivium CompactStat.e10800 provided a mobile potentiostat for field EIS. The standard measurement parameters were 10^5 to 10^{-2} Hz at 10 points per decade with voltage perturbations of 10 mV around the open circuit potential (OCP).

Laboratory Investigation of Vinyl Field Results

A 3" x 6" mild steel panel coated with a solution vinyl coating system provided comparison testing. The coated coupon had been immersed in a tank of flowing deionized water at room temperature for 8 years. Records show the steel panel had been solvent-cleaned and abrasive blasted to a white metal grade recommended surface cleaning and abrasive blasting were performed prior to application of (15). The vinyl was first tested as is, without visible imperfections. The testing surface area for this experiment was 20 cm^2. Data was adjusted to the surface area of the field data for direct comparison of the measured current. Three defects were created in adjacent testing surfaces in an attempt to reproduce the defect in Test 2.2. The defects were approximately 0.039%, 0.020%, and 0.002% of the total surface testing area.

The panel was prepared for EIS measurements in the following manner: a glass cylinder was clamped to the coated panel and sealed using an *o*-ring to prevent leakage. DHS solution was added to the glass cylinder. The reference electrode and counter electrode were also placed inside the test cell. A saturated calomel electrode (SCE), platinum mesh, and steel substrate were used and the reference, counter, and working electrode, respectively. Refer to Figure 2 for this test cell set up.

A Gamry Instruments FAS2 Femtostat performed the potentiostatic EIS experiments with EIS300 software. The EIS test applied 10 mV perturbations across the coating film using the open circuit potential as the mean applied voltage. The test recorded the current required to satisfy this voltage pattern. The frequency ranged from 10^5 to 10^{-2} Hz at ten points per decade.

Regular EIS testing was performed to evaluate the influence of the defects on the data. Between testing, the coated coupon received exposure to salt fog in accordance with ASTM G85

Annex A5 (16) to expedite the degradation of the coating matrix and produce iron oxides in the defect area. The coating was tested daily for a week and then twice weekly as degradation patterns began to normalize.

RESULTS AND DISCUSSION

Coated Infrastructure Inspection Results

Test 1.1 measured a horizontal surface on the top face of the gate, as shown in Figure 3. No defects were apparent within the test cell. However, numerous impact defects were in the vicinity. The (OCP) was approximately -0.400 V vs SCE. The actual OCP of the steel varies based on environment—for example, -0.600 V to -0.700 V vs SCE is typical for flowing seawater. The coating provides resistance in this measurement technique, causing the data to be higher. Measurements of 0.200 to 0.00 V are common for a new coating.

The measured impedance for Test 1.1 was nearly 10^{11} Ω at the low frequencies. The EIS data is most easily interpreted by viewing the impedance, |Z|, at low frequencies (less than 10^{-1} Hz). This value represents a coating's total resistance to corrosion. Low frequency impedance must be 10^6 to 10^7 Ω to provide reasonable corrosion protection (17-18). In Figure 3, the colored strip at the left designates coating condition by green-yellow-red as good-moderate-poor, respectively. This color theory is created to suggest that recoating planning begins when the measurement approaches the red region of the plot. This designation can be adjusted to meet an agency's or facility's approaches to corrosion protection. For example this color band can be shifted upward and the yellow section compressed if superior corrosion protection is required.

The data for Test 1.1 contains a high degree of scatter—this is especially apparent in the phase angle data. Possible reasons for this include noise, coating/solution instability, and resistances that exceed the instrument's capacity. Furthermore, an impedance value this high (10^{11} Ω) is not realistic for a weathered coating. It was concluded that the contact resistance of the circuit was too high. A cellular device was also operating within several meters of the test cell.

This test was measured before the epoxy adhesive cured. Gorilla Tape was used to hold the epoxy in place. It is assumed that neither affected the data significantly.

Test 1.2 (not shown) measured a vertical surface on the upstream splash zone skin plate. There were no obvious defects however a close inspection was not made. Numerous coating defects resulting from impacts were in the vicinity of this test cell as well. The measured impedance was 10^5 Ω at the low frequencies, which is more realistic for this type of system. At this frequency, it is likely that small permeations are present through the film, and the coating has surpassed its useful service life.

Test 2.1 measured a horizontal surface on an angle iron that receives atmospheric exposure. The coating system is a red lead linseed oil primer with a phenolic aluminum topcoat. No defects were apparent within the test cell. Figure 4 shows the impedance data which provides smooth curves and no scatter. This is ideal EIS data, and the basic interpretation suggests that recoating is needed. Further investigation is needed to determine the impact of aluminum in this coating, which reduces the circuit resistance as a conductor. Laboratory data on this coating system is not currently available.

Test 2.2 measured a horizontal surface on the Tainter gate arm, near the trunnion pin. Figure 4 provides the test setup and data. This coating contained standing water due to a plugged drain hole. The drain was cleared and the water removed to evaluate the coating. Afterward small rust stains indicated numerous pinhole defects in this test area. One defect was isolated in the test cell. The defect was not measured but is estimated to be less than 1 mm^2.

The $|Z|_{0.01\ Hz}$ measured $10^7\ \Omega$ for Test 2.2. The test was set up to measure 5 data points per decade, resulting half the data points. The resulting data shows minimal scatter and is sufficient to conclude that the test results are accurate and realistic. Using the colored strip, this coating is currently providing adequate corrosion protection. Taking the pinhole into consideration, which provides a low resistance pathway, the coating film is in good condition.

Test 2.3 measured a vertical surface on the upstream face of the miter gate (Figure 5). The instrument terminated the measurement before completing due to resistances exceeding the instrument's capacity. A poor substrate connection was attributed to this, and, therefore, no coating data is available.

Laboratory Vinyl Results

A small laboratory test validated the field results obtained by the vinyl coating evaluated in Test 2.2. This coating system was chosen because it was known and because a weathered laboratory system could be obtained. Here, the vinyl laboratory sample is thought to be an exact match for the field coating system—gray-white-gray vinyl—and is documented to be in its 8th year of exposure in a deionized water immersion tank.

The laboratory sample had no visible defects, and the preliminary EIS measurement indicated strong barrier protection. The sample behaves much like that of a capacitor and $|Z|_{0.01\ Hz}$ was 7.2 x $10^9\ \Omega$. The phase angle data (not shown) shows a 90 degree phase lag for all frequencies.

A series of defects served to better match the field results to the laboratory coating. The application and weathering of three defects of varying size resulted in distinctly varied data. The defects are characterized as a medium defect, small defect, and pinhole. Table 2 summarizes the surface area, derived through Image J analysis, of metal substrate exposed for each of these defects. It also provides the relative defect area to the total measurement area and $|Z|_{0.01\ Hz}$.

Figure 10 provides the laboratory vinyl impedance data for all frequencies. The field data is also included. Due to differences in the measurement surface area, the field data required a correction factor for direct comparison. Since the field and laboratory measurement areas were 25 cm^2 and 20 cm^2, respectively, a factor of 25/20 sufficed. The field data trend line in Figure 10 falls in-between the pinhole and the small defect. This allows the conclusion to be drawn that the size of the field defect is between 0.020% and 0.002%. Furthermore, the shape of field data trend line, compared to the laboratory results, validates the accuracy of the field measurement itself.

Evaluation of Field Methodology

Through field demonstrations, it has been shown that a mobile potentiostat can provide accurate data for coated infrastructure in the field. Although no Faraday cage is needed, several precautions can be taken to ensure the data will have no or minimal noise. The most obvious sources of noise include cellular emitting devices and AC electrical sources. Therefore, turn cell phones and other devices to airplane mode and do not charge/power laptop computer while EIS measurements are in progress. The steel structure may provide some Faraday cage effect. For example, in Figure 4 the test cell is shielded on three sides from noise sources.

With regards to the test cell set up, the testing to date has shown that the substrate connection is the most critical element for a successful field test. Should the connection be poor, significant contact resistance will measured at this part of the circuit. It is difficult to separate from the resistances of the coating itself and the impedance data will be artificially high. Therefore, to ensure a strong substrate connection, file the steel contact point to remove oxides. Once the surface is clean, maximize the contact surface area and be sure to use a high conductivity connection material, such as copper wire. In the experiments shown here, an alligator clip was taped directly to the steel surface. Additional testing has shown copper wire attached to a jumper provides more consistent results. The inspector can ensure the connection is good by reading the OCP preview in the software or using a standard multimeter. This potential should not change or drift more than a 1 mV during a 10 second preview.

If an inspector observes consistent potential drift during an open circuit potential preview, a grounding rod may provide relief. This has yet to be evaluated experimentally.

Coating type, exposure conditions, saturation level, access, and surface geometry/orientation should be evaluated for any EIS field inspection. The following advice is offered for each:

- Coating type—more hydrophobic coatings have higher impedance values for coatings, assuming minimal weathering. Coatings with a higher degree of hydrophilic moieties may have impedance values slightly lower. Laboratory testing shows that a 20 mil coating of polyurethane may be have $|Z|_{0.01\ Hz}$ near $10^{10}\ \Omega$ whereas and epoxy of the same thickness is closer to $10^{9}\ \Omega$. These laboratory baseline tests are important to determine the realistic range of coating impedances when interpreting field data. This coating impedance decreases as the coating degrades.
- Exposure conditions—the goal of this EIS field method is to measure the general condition of the coating in an area with no visible defects. Furthermore, the worst case scenario (severe exposure) is more useful than an area of the structure that receives minimal weathering. Measurements at and/or beneath the waterline are ideal to evaluate the coating condition resulting from these harsh conditions. In this paper, the Tainter gate arm appears to cycle wet-dry exposure, which should show more degradation than the parts of the gate with atmospheric-only exposure.

- Saturation level—a saturated coating system presents an opportunity to measure EIS quickly because the coating/solution is already stabilized. Again, the Tainter gate arm provided standing water at the time of inspection.
- Access—this field method requires intimate access to approximately 1 ft^2 of coating surface. Furthermore, space must be available within the 3-foot cord length to arrange the testing equipment for approximately 30 minutes. A connection to the steel substrate is also required. Ideally, this connection should be made near to the test to minimize total circuit resistance.
- Surface geometry/orientation—the current method uses an inverted plastic beaker; therefore, flat surfaces are required to obtain a good seal for the test cell. Although not tested, it may be possible to use test cell with a caulking material in small to medium diameter pipes. Otherwise, a different test cell is needed for curved surfaces. Horizontal surfaces provide the easiest application of test cells. A vertical surface can be tested but it is difficult to know that the entire coating surface is in contact with the solution. A modified test set-up, such as the incorporation of conductive gels, could improve the ease of applying the test to non-horizontal surfaces.

To facilitate incorporation into maintenance inspections, the field EIS method developed at Reclamation will be published as a technical memorandum (19). Furthermore, additional field demonstrations, troubleshooting, and publication developments are underway.

CONCLUSIONS

The focus of this paper was to validate a test method for field application of EIS using low cost and accessible materials. Field trials were demonstrated on U.S. Army Corps of Engineers projects at Ozark-Jeta Taylor Lock and Dam and Wilbur D. Mills Lock and Dam along the Arkansas River. This field application proved successful with many lessons learned. For example, it is critical that all significant resistances are minimized in the test circuit to isolate the coating film. A method of assigning relative protection is presented as a red-yellow-green colored strip in the test data. This information can assist managers in maintenance planning. Furthermore, information is provided to select ideal test sites at facilities.

The field application of EIS would supplement the current qualitative evaluations methods. The advantage of this test method is quantitative data to assess the general coating condition before degradation is visible. Additional work will continue to transition EIS into coatings inspections.

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Tables

Table 1. EIS field demonstration information

#	Location	Coating	Service	Test Cell Condition	Position
1.1	Top edge of radial gate*	Vinyl	Atmospheric	No visible defects—Adjacent impact defects	Horizontal
1.2	Upstream skin plate of radial gate*	Vinyl	Splash zone	No visible defects—Adjacent impact defects	Curved, vertical
2.1	Angle iron by handrail^	Red lead linseed oil primer & phenolic aluminum topcoat	Atmospheric	No visible defects—Adjacent rust staining and exposed red lead primer	Horizontal
2.2	Gate arm near trunnion pin^	3-coat vinyl (gray-white-gray)	Atmospheric & immersion	One visible pinhole within test cell—adjacent pinholes	Horizontal
2.3	Upstream skin plate of miter gate^	3-coat vinyl (gray-white-aluminum)	Atmospheric	No visible defects	Vertical

* USACE Wilbur D. Mills Dam
^ Ozark-Jeta Taylor Lock and Dam

Table 2. Laboratory vinyl defect data and results

Test	Surface Area (mm^2)	Relative Area (%)	$\|Z\|_{0.01\ Hz}$ (Ω)
No defect	-	0	7.2×10^{9}
Medium defect	1.0	0.039	3.6×10^{4}
Small defect	0.5	0.020	1.5×10^{5}
Pinhole	0.05	0.002	9.4×10^{7}
Test 2.2 (field)	?	?	1.2×10^{7}

Figures

Figure 1. Ozark-Jeta Taylor Lock and Dam location for inspection with mobile potentiostat

Figure 2. Laboratory EIS test cell in Faraday cage

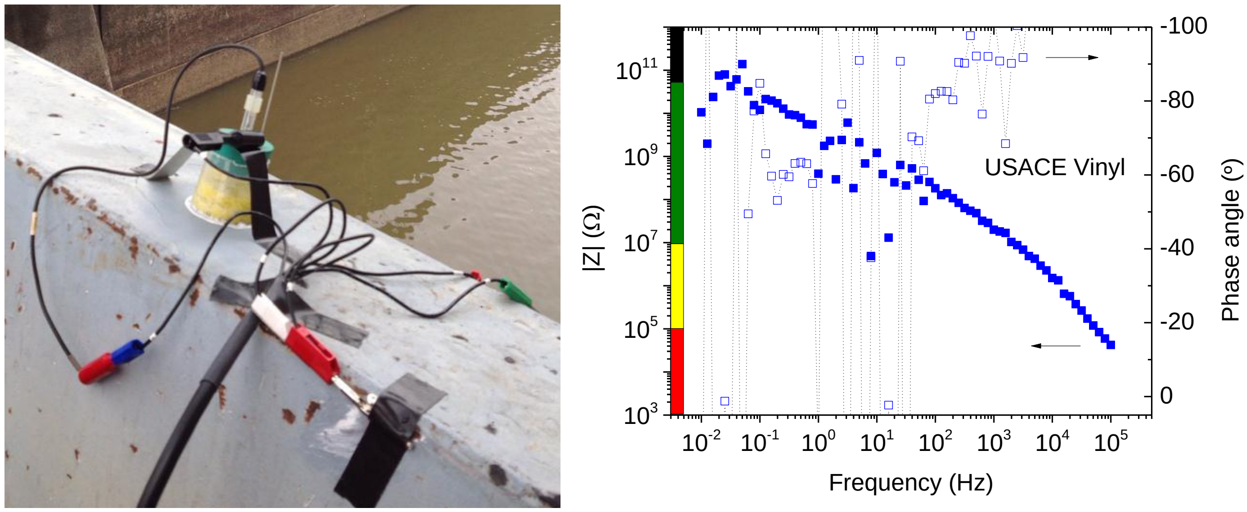

Figure 3. Field EIS Test 1.1 set-up (left) and results (right) for top face of USACE Tainter gate

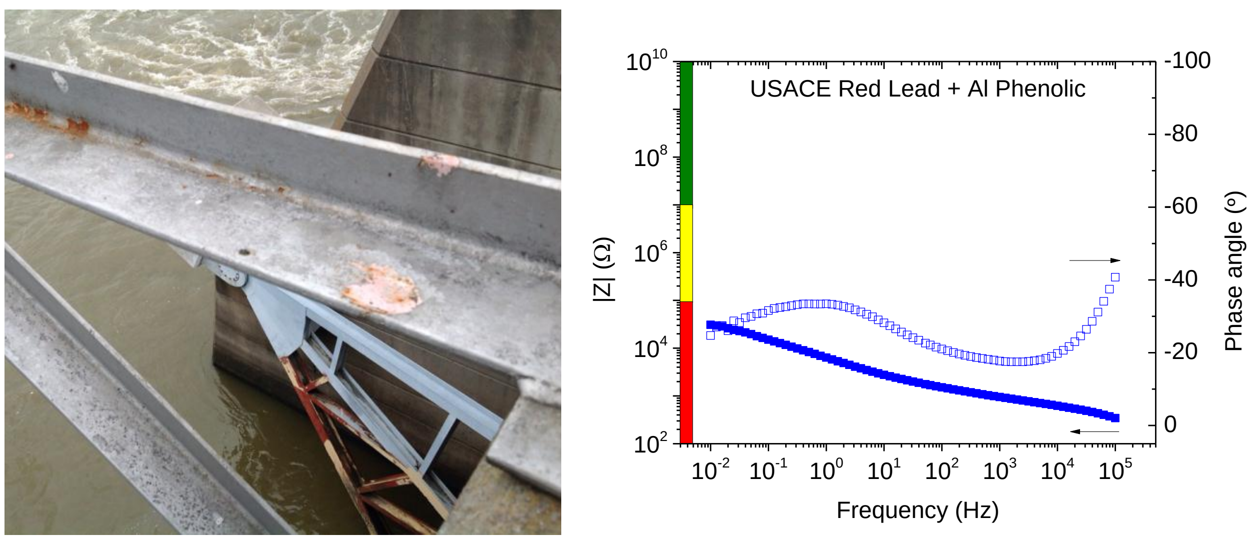

Figure 4. Field EIS Test 2.1 red lead primer with aluminum phenolic topcoat

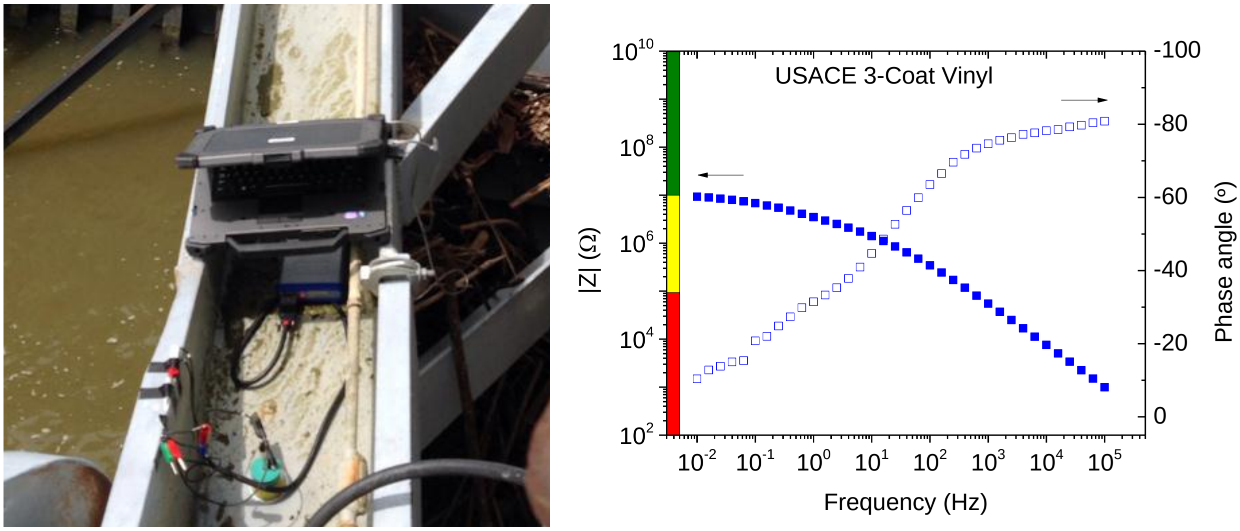

Figure 5. Field EIS Test 2.2 set-up (left) and results (right) for USACE Tainter gate at trunnion arm


Figure 6. Field EIS Test 2.3 set-up on upstream face of miter gate

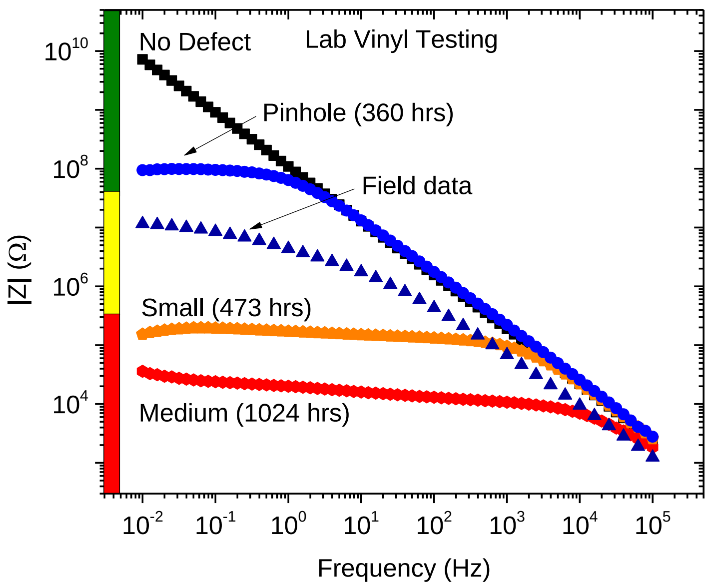

Figure 7. Laboratory EIS results with and without coating defects; the defect size descends in the order of medium, small, and pinhole